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USING A HIGH-VALUE RESISTOR IN SINGLE-ELECTRON COUNTING MEASUREMENTS

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Abstract

An experiment using a high-value cryogenic resistor is proposed, with the aim of improving the experimental link between three quantum electrical standards. This technique is new in its approach and does not require feedback from either a voltage detector or a current detector. Performance is limited by fundamental resistor and SQUID detector noise.

Introduction

Several ways have been suggested to experimentally combine the Josephson effect (Josephson constant $K_J = 2e/h$), the quantum Hall effect (von Klitzing constant $R_K = h/e^2$), and the counting of single electrons in "metrology triangle" experiments. Experiments in this vein based on cryogenic capacitors have reached an uncertainty level of a few parts in a million [1], but are ultimately limited by knowledge of the quantized Hall resistance (QHR) to relative uncertainties of about 3×10^{-8} .

Results beyond this level of uncertainty would provide better tests, using Ohm's law, of mutual consistency between experimental values of fundamental constants. This experiment proposes to directly monitor a balance between small currents produced from two of the three quantum effects. The balance is set up between current passing through a cryogenic resistor induced by the voltage from a Josephson voltage standard (JVS) and current generated by a single-electron tunneling (SET) pump device. Limits on the signal-to-noise ratio in this experiment are set by the level of current provided by the SET device, Johnson noise and temperature dependence in the resistor, and the noise in a superconducting quantum interference device (SQUID) used as a detector.

Noise considerations show that the resistor value should be on the order of 100 M Ω or higher for use with good commercial SQUIDS. NIST has begun development of

metallic thin-film resistors using silicon copper alloys. These devices have relatively low temperature dependence at cryogenic temperatures, and can be made reasonably small even at this resistance level. NIST plans to continue this research on thin-film resistors and characterize noise contributions and temperature dependence down to 20 mK.

Circuit Description

The current-detection phase of this experiment uses a circuit as shown in Fig. 1. A programmable JVS system provides a known voltage at one end of the cryogenic resistor. A superconducting winding ensures that the low side of this resistor is almost precisely at dc ground. The JVS and SET pump are arranged to produce nearly equal currents i_R and i_S , and these quantum electronic sources ($i_S = f_{SET}e$, $V = n f_{JVS}/K_J$) can be reversed simultaneously. The superconducting winding is coupled to a SQUID (not shown) that detects the difference current i_Δ .

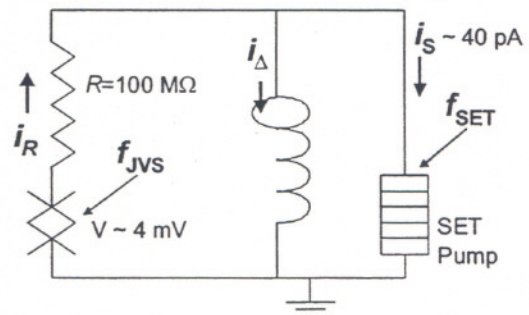


Fig. 1. Current-detection circuit

While the superconducting winding in Fig. 1 is essentially a cryogenic null-detector for current, this main cryogenic winding also acts in another capacity. A cryogenic current comparator (CCC) with other superconducting windings (shown in Fig. 2), based on one proposed by Sullivan and Dziuba [2], serves to calibrate the cryogenic resistor. The circuit parameters given in Fig. 1 assume a major technological step, namely that future SET pumps can

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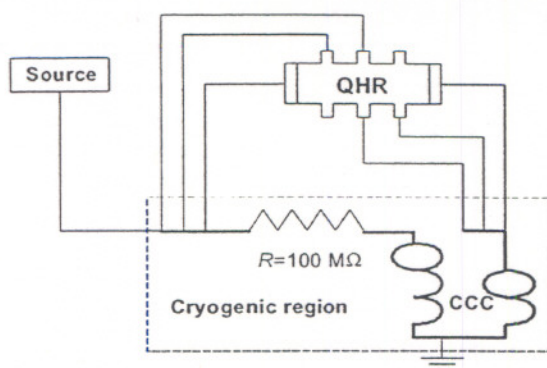


Fig. 2. Circuit of cryogenic bridge used to calibrate the cryogenic resistor. Connecting wires in the cryogenic region are superconducting to eliminate voltage differences affecting the bridge. Triple-series connections reduce the effects of resistance in leads and device contacts of the QHR device.

supply currents about 10 times higher than today's best metrological devices. Any increase is helpful because it improves the resolution; in this case higher current also would help satisfy $V = IR$ in this circuit for the following reasons: the smallest voltage step output of existing programmable JVS sources is about 4 mV, and values of resistance significantly greater than 100 MΩ would require lithographic patterns for the resistor with dimensions greater than 1 cm on a side.

The circuit of Fig. 1 has some advantages over suggested comparison experiments using a CCC, JVS, SET pump and QHR standard in a single circuit [3]. First is that the QHR device needs to be used only for short periods of time. The cryogenic resistor can be calibrated at higher currents than that provided by the SET pump, assuming characterization of loading effects. Second, neither part of the experiment requires a voltage detector. This eliminates one external source of noise. Third, feedback that might contribute to excess noise and flux-jump behavior is absent in the current-detection phase, which does not use a CCC. This design of the experiment is more immune to disturbances and can be run without supervision for extended periods of time, to benefit from statistical reduction of noise.

Transient-recovery characteristics of the circuit are also of importance because of strongly frequency-dependent noise in SQUID sensors. The full difference current i_d to be measured by the primary winding in Fig. 1 can be made arbitrarily small. Thus, only the settling time for transient signals is significant. The impedance of the detection winding should not be significant if resonant circuit effects can be avoided in the circuit design. We estimate that charging effects due to stray capacitance in the cryogenic resistor will have a time constant of order

1 ms. Thus, capacitive currents and transients generated in the reversals would probably be negligible in fast-reversed dc signal detection after delays of 25-50 ms. Reversal rates of 5-10 Hz would allow the SQUID to be operated near its high-frequency white noise limit.

Developmental Strategy

Measurements of high-value resistors in terms of the QHR are an important step in development of this experiment. Some thin-film resistors of value about 10 kΩ have been produced and characterized. Resistors near 1 MΩ are being developed at NIST and will be characterized in a dilution refrigerator. The cryogenic resistor at variable substrate temperature ($T \geq 20$ mK) will be compared to a QHR device located in a separate cryostat. Mesoscopic physical processes (electron-electron interactions and weak localization) may contribute to the electronic noise properties of the resistors at low temperatures.

A CCC based on the design in Fig. 2 has been tested at 4.2 K, with measured sensitivity better than $3 \mu\text{A-turn}/\Phi_0$. The ratio of this CCC is 1937:25. Using additional build-up windings, the CCC can be used for comparing cryogenic resistors of values 600 kΩ – 1600 kΩ to the QHR. It is also possible to use a reference resistor other than the QHR if larger uncertainty due to lead resistance is acceptable. Cryogenic resistors of higher value could be characterized using wire-wound external resistors as the fixed standard.

The development and testing process for this type of CCC is likely to lead to some benefits in uncertainty for scaling to the 1 MΩ resistance level at NIST. A second CCC similar to that shown in the diagram of Fig. 2 has been built to aid in scaling, based on the QHR, for calibrations of room-temperature 1 MΩ resistors.

References

- [1] M. W. Keller, A. L. Eichenberger, J. M. Martinis, and N. M. Zimmerman, "A Capacitance Standard Based on Counting Electrons," *Science*, Vol. 285, pp. 1706-1709, Sept. 10, 1999.
- [2] D. B. Sullivan and R. F. Dziuba, "A Low-Temperature Direct-Current Comparator Bridge," *IEEE Trans. Instrum. Meas.*, Vol. 23, No.4, pp. 256-260, Dec. 1974.
- [3] Y. De Wilde, F. Gay, F. Piquemal, and G. Geneves, "Measurements of Single Electron Transistor Devices Combined with a CCC: Progress Report," *IEEE Trans. Instrum. Meas.*, Vol. 50, No.2, pp. 231-234, Apr. 2001.